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Thermoelectric cold-chain chests for storing/ transporting vaccines in remote regions

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Abstract

The cold chain is one of the key elements of the preventive health-care delivery system. Vaccines have to be carried long distances, stored in remote places and during this period the temperature has to be maintained within certain specified values. Realizing the needs of such requirements, the Department of Science & Technology, New Delhi (Govt. of India) assigned a project to the R&D Division of MECON, Ranchi for development of Thermoelectric Cold-Chain Chest operated by 12 V DC vehicular battery. The resulting portable thermoelectric (i.e. Peltier effect) Cold-Chain Chest (TCC) operated successfully even in an ambient environment of 45 °C, mainly for preserving and transporting life-saving medicines for urban as well as rural areas.

Keywords: Thermoelectric; Cold Chain; Peltier effect; Solid-state heat pump

1. Introduction

MECON's in-house Research & Development Division has conducted thermoelectric research for more than 15 years [1–20]. Thermoelectric Cold-Chain Chests (TCCs) developed under the present project have simple structures, high reliabilities, low power consumptions and are suitable for use in medical and health-care programmes for storing and/or transporting medicine, drugs, vaccines, serum, semen and diagnostic materials. Administering vaccines to prevent diseases in children is an important component of the preventive-care system. In India, the immunization programme for children places emphasis on three vaccines: polio vaccine (oral form); the combined Diphtheria/Pertussis/Tetanus (DPT) (injectable) vaccine and the Measles/Mumps/Rubella Vaccine (MMR) (injectable) vaccine. These vaccines are biological products and require storage at prescribed low temperatures to maintain their effectiveness.

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Once potency has been lost through exposure to heat or cold, it cannot be regained by returning the vaccine to the correct storage temperature. If potency is lost through heat exposure, vaccines do not change their appearance, so it is not possible to see the difference between a potent and an impotent vial of vaccine without a full laboratory test. It is therefore very important to ensure that the vaccine is maintained within the specified temperature range at all times after manufacture to the time it is administered. In this context, the term "Cold Chain" has come into usage to refer to the system of storage and transport of vaccines at low temperature from the manufacturer to the site where the vaccines are used.

Thermoelectric cooling has been proposed to provide the required cooling when the vaccine is being transported to remote areas in small lots and stored in remote places, and its implementation in various forms has considerable potential.

Thermoelectric cooling is based on the Peltier effect in which when a current is passed around a circuit of different materials; one junction gets heated while the other junction is cooled. By reversing the direction of current flow, the heating and cooling of the two junctions are mutually interchanged. Thermoelectric modules are small solid-state heat pumps, which transfer heat energy according to the laws of thermodynamics. In this regard, the semiconductor (Bi_2Te_3) is recommended for the thermoelectric modules. At the cold junction, heat is absorbed by electrons as they pass from a low energy level in the p-type semiconductor element, to a high energy level in the n-type semiconductor element. The external power-supply provides the energy to move the electrons through the system. At the hot junction, energy is expelled to a heat sink as electrons move from a high energy level element (n-type) to a lower energy level element (p-type). In a thermoelectric cold chest (TCC), the cold junction of the module is used to extract heat from the chest and maintain it at a low temperature. Such TCCs are totally solid state, do not use a working fluid or compressor, are intrinsically CFC free and suitable for environmentally-safe systems.

This paper reports the technical approach, functioning of components and performance characteristics of different types of TCCs designed for the following applications.

i) Maintaining $+2$ °C internal temperature
ii) Simultaneously maintaining two different internal zones i.e. at $+2$ °C and -9 °C
iii) Maintaining an internal temperature of -17 °C.

All the designs are based on an ambient environment at 45 °C. Such chests are rugged, high impact cases with tight sealing lids, insulated by PUF and operated by 12 V DC. All temperatures are controlled/maintained by a special electronic circuit fixed on the walls of the chests.

A provision is kept for mounting a back-up rechargeable Nickel-Metal-Hydride (NimH) battery system on the back side of the TCC for providing uninterrupted power for up to 60 min, when the main 12 V DC battery is detached from the TCC as is likely to happen when the TCC is shifted from the vehicle to the health centre or vice versa.

2. Technical approach

2.1. Description of Cold-Chain Chests

This paper reports on three different types of TCCs:

Type I chest is made as a single compartment, with an internal capacity of 2.5 l. The internal average temperature is maintained at +2 °C with the ambient temperature of up to 45 °C.

Type II chest is made as a double compartment chest. One compartment, of internal capacity 1.0 l, is maintained at an internal average temperature of −9 °C and the other compartment, of internal capacity 1.5 l, is maintained at an internal average temperature of +2 °C with the ambient temperature of up to 45 °C.

Type III chest is made as a single compartment of internal capacity 2.5 l. The internal average temperature is maintained at −17 °C, with the ambient temperature of up to 45 °C.

A typical view of a single compartment chest (for +2 °C or −17 °C) is shown in Fig. 1 and a typical view of the double compartment chest (i.e. +2 °C or −9 °C internal temperature) is shown in Fig. 2. The chests are of double-walled construction, with a hinged cover and one or two windows provided on opposite walls of the compartment to facilitate mounting the thermoelectric modules as shown in Figs. 1 and 2. The space between the walls is filled with polyurethane foam (PUF). A sealing gasket is provided on the topside of the compartment and the lid sealing engages with this. Latches are used on the box for tightly securing the lid to the compartment.

The fixing of suitable thermoelectric modules, combined with a cold sink, spacer block, thermal insulation foam, hot sink and fan on opposite walls of the cold

Fig. 1. Typical view of single compartment +2 °C or −17 °C thermoelectric cold-chain chest.

Fig. 2. Typical view of double compartment (+2 °C/−9 °C) thermoelectric cold-chain chest.

compartment, ensures an almost uniform temperature distribution exists inside the compartment.

A typical isometric exploded view of the thermoelectric cooler assembly for such chests is shown in Fig. 3.

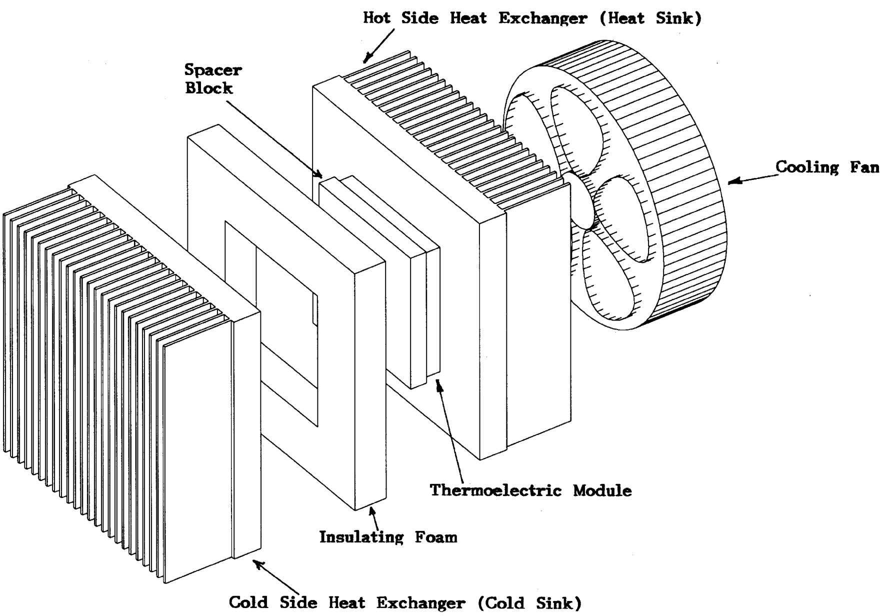

Fig. 3. Typical isometric exploded view of thermoelectric cooler assembly.

2.2. Selection of thermoelectric module

Proper selection of the thermoelectric module is critical to the performance of the TCC. Selection of thermoelectric modules to pump a certain amount of heat at a certain voltage and current depends on several factors. For instance, the size of semiconductor elements determines the maximum current draw and the number (N) of elements determines the maximum voltage. This size relationship is commonly referred to as the geometry factor (G) of the module defined as

$$G = \frac{\text{Area} \quad (\text{cm}^2) \quad \text{of} \quad \text{the} \quad \text{element}}{\text{length} \quad (\text{cm}) \quad \text{of} \quad \text{the} \quad \text{element}} \tag{1}$$

Together N and G determine the maximum heat-pumping capacity ($Q_{\max}$) of the overall module.

Most thermoelectric modules are specified by the following parameters, $I_{\max}$, $V_{\max}$, $Q_{\max}$ and $\mathrm{DT}_{\max}$, where $Q_{\max}$ is the maximum amount of heat that will be pumped at $I_{\max}$, at $\mathrm{DT}=0$. Conversely, $\mathrm{DT}_{\max}$ is the maximum temperature differential achievable across the module at $I_{\max}$, when $Q=0$. This implies that Q and DT carry an inverse relationship.

So, for a given input power, as DT increases, Q will decrease and vice versa. In a cold-chain chest application, the minimum value of DT is the difference between the ambient temperature and the cold-chamber temperature. The actual value of DT is higher than this minimum: hence

i) the hot side of the module will have a temperature several degrees higher than ambient; and
ii) the cold side of the module will have a temperature a few degrees below the average temperature of the chamber and the operating value of DT can be estimated correctly only if the interrelated heat-transfer phenomenon is estimated correctly and the dependence of the heat pumping rate Q on DT is also estimated accurately.

A computer model was developed for simulating the relationships and selecting the thermoelectric module that best meets the requirements.

Thermoelectric modules have their own physical limitations for attaining DT. For our case, single-stage thermoelectric modules have limitations up to 67 °C DT across the elements. Hence to achieve more DT (i.e. more than 67 °C) one has to stack thermoelectric modules one on top of another. By stacking the modules, one can theoretically create two or more element levels that can have this 67 °C DT. In effect, the first stage lowers the hot-side temperature of the next stage, which in turn has a 67 °C DT and so forth. While each level acts like a single-stage module, the overall system may show a DT 2 or 3 times that of a single-stage module. Therefore, by stacking the modules one can achieve a much larger DT, but at the expense of a lower overall $Q_{\max}$. Hence, for our system, as the desired internal temperature of the TCC decreases, we used more double-stage modules that cannot only pump more heat, but pump more heat at a larger DT. That is why we shift from a single-stage

module for +2 °C TCC to a large multi-stage module for −9 °C TCCs. Two multistage modules were used for −17 °C TCCs to increase the pumping capacity and achieve a large DT.

The coefficient of performance 'COP' explains the overall efficiency of a thermoelectric module and concerned TCCs, which is explained as

$$\text{'COP'} = \frac{\text{Heat pumped at cold junction}}{\text{input power}} = \frac{QC}{Q_{\text{in}}} \tag{2}$$

As the heat load rises, one has to increase the power to the module to compensate. However, eventually in our TCC, we increased $I_{\max}$ of the module in order to pump more heat and this reduces the 'COP'. To alleviate this problem, we used two modules for the single chest. These two modules can pump the same amount of heat at a lower percentage of $I_{\max}$ than a single module. So by choosing two modules instead of a single module, one can increase the efficiency of the TCC.

Details about the thermoelectric modules used in the different types of TCCs are given in Table 1.

2.3. *Assembly of thermoelectric-cooler unit*

The thermoelectric module was assembled between the heat sink, cold sink and spacer block with a heat insulating seal (foam) between the two sinks as shown in Fig. 3. The entire assembly is mounted on one side wall of the compartment.

A spacer block is mounted between the cold face of the thermoelectric module and the cold side of the cold sink. The cold sink is insulated from the spacer block and thermoelectric module by the heat-insulating foam. The heat sink is mounted on the other side of thermoelectric module, i.e. remote from the cold sink. A fan is mounted directly on the heat sink to provide forced-air convection to the heat sink, if and when required. This ensures that the hot junction temperature does not exceed the design value.

A small temperature controller is mounted on the outside of the wall of the compartment. This temperature controller was connected to the thermoelectric module, fan and to a D.C. power supply. Ten rechargeable 1.2 V and 4500 mAh

Table 1
Bi_2Te_3 thermoelectric modules used in the different types of TCCs tested

Type of TCC	No. of chambers	Chamber capacity	Chamber temperature (°C)	No. of modules	No. of stages	Geometry factor	COP	No. of couples
I	1	2.5	+2	2	1	0.121	0.26	127
II	2	1	−9	1	2	0.179	0.21	190
		1.5	+2	1	1	0.118	0.26	127
III	1	2.5	−17	2	2	0.171	0.12	190

small NimH batteries (of size: OD ≅ 26 mm, $H \cong 50.5$ mm and weight ≅ 90 g) are connected in series (as a package) on the back wall of the TCC as UPS. This will provide power to the TCC when it is temporarily disconnected from the power supply during transit (Fig. 4).

2.4. Function of each component

A thermoelectric module works on the principle of the Peltier effect, in which, when a current is passed-around the module, one side gets cooled while the other side is heated. This cold side of the module is used to cool the vaccine chamber. Cooling is transmitted through the spacer block and cold sink to inside the chamber of the compartment. The use of a spacer block ensures a high rate of heat transfer, while at the same time separating the heat-sink side from the cold-sink side of the system.

Thermal-insulating foam is used for inhibiting the back flow of heat that often occurs when operating at or below the dew point or in humid conditions. The hot-side heat-sink is used to dissipate heat generated by the hot-side thermojunction. A DC fan is used to provide forced-air convection to the heat sink if needed. Heat dissipation at the hot side is important because the thermoelectric modules are characterised in terms of maximum temperature difference between the hot and cold junctions: higher temperatures at the hot junction limit the minimum achievable temperature at the cold junction. Also the thermoelectric modules tend to deteriorate if the hot-side temperature exceeds certain values.

The temperature controller in such a system plays a vital role, because temperatures lower than a specified minimum also change the vaccine. The temperature controller provided reduces the current (to one-third of the full current) supplied to

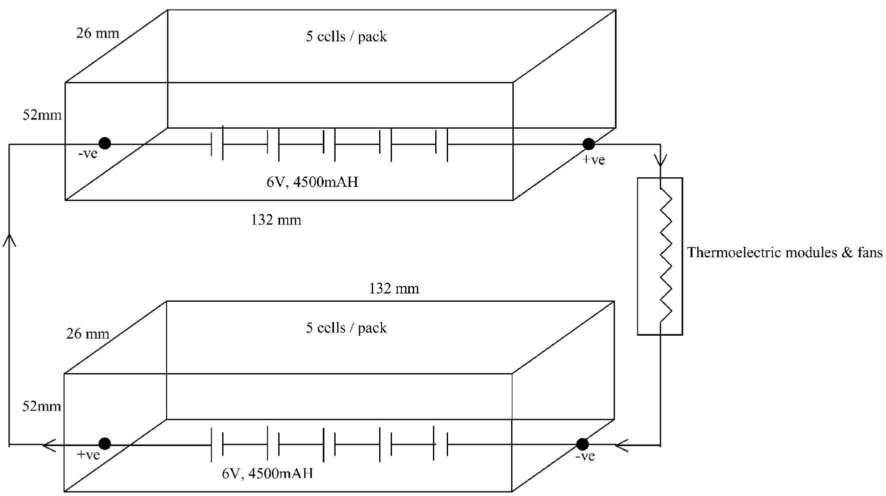

Fig. 4. Schematic arrangement of batteries in battery pack as a backup for the thermoelectric modules, fans and temperature controller.

the thermoelectric module of the compartment when the chamber temperature reduces the lower limit of the control band. When the temperature inside the box rises to the upper limit of the control band, the temperature controller acts to increase the current supply to the modules to the set value.

A typical arrangement is made with 10 1.2 V and 4500 mAh small NimH rechargeable batteries with thermoelectric modules and fans through the temperature controller, for providing at least 60 min of power to each compartment (after reaching the designed temperature of the TCC) as and when the main 12 V DC source is not available. By providing such UPS, the overall dimensions of the TCC are not going to change, but only the overall weight will increase to around 900 g of each TCC. Such a TCC hybrid with main 12 V DC batteries along with a small portable UPS may maintain completely the potency of the vaccines.

3. Performance characteristics

These thermoelectric modules were operated by 12 V DC. Temperatures inside the chests were recorded by fixing thermojunctions of a 16 channel ADAM-4018 temperature scanner to randomly placed ampules inside the chests. Two thermojunctions were fixed on to the hot-side heat-exchanger. One thermocouple was used to monitor the ambient temperature. Thermocouples of the above scanner were T-type (copper/copper–nickel) welded tip T/C wire, RS, Model: 219-4696 and the scanner was connected to a Pentium PC. Ambient conditions corresponding to 45 °C temperature were created by enclosing the chest inside a perspex chamber and utilizing the heat generated by the hot junction to increase the ambient temperature.

For Type II chests, the initial current requirement for both the chambers was recorded as 7.0 amps. After reaching the desired temperatures, i.e. −9 °C and +2 °C respectively, the temperature controller connected with the thermoelectric modules reduced the current of the modules to one-third of its full current until the inside temperature again rose to either −8 °C or +3 °C in the respective chambers. The objective of passing the one-third current through the respective thermoelectric modules (after reaching the desired temperature) was to prevent a back flow of heat from the hot-side heat-exchanger to the cold face which would occur if the current was switched off. Typical results under different conditions are shown in Figs. 5–7.

Fig. 5a represents temperature versus time characteristic of −9 °C and +2 °C of the double-door thermoelectric cold-chain chest, where the ampules temperatures are recorded for ampules randomly placed inside the chamber (with an ambient environment of 45 °C). It is seen that for the +2 °C chamber, the internal temperature +2 °C was reached after 120 min of operation and was maintained within +3 °C to +2 °C during the remaining period of experiments i.e. up to 300 min. Similarly for −9 °C TCC, the internal temperature of −7 °C to −11 °C was reached after about 120 min of operation and was maintained within this range during the remaining period of the experiment. It is clear from the above that the TCC needs to be precooled for about 2 h (under an ambient temperature of 45 °C) before the vaccine is transferred to it, but the temperature is maintained within a narrow band thereafter.

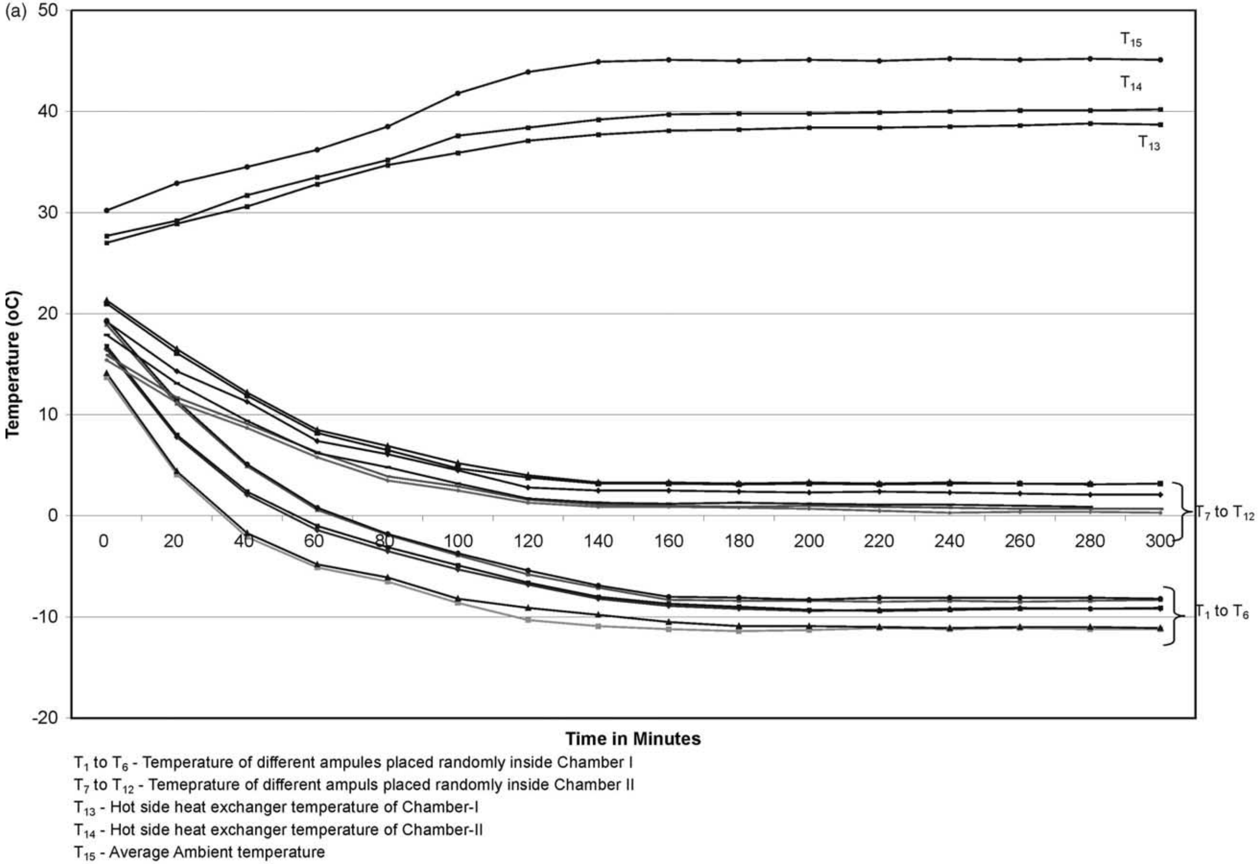

Fig. 5. (a) and (b) −9 and +2 °C double door thermoelectric cold-chain chest.

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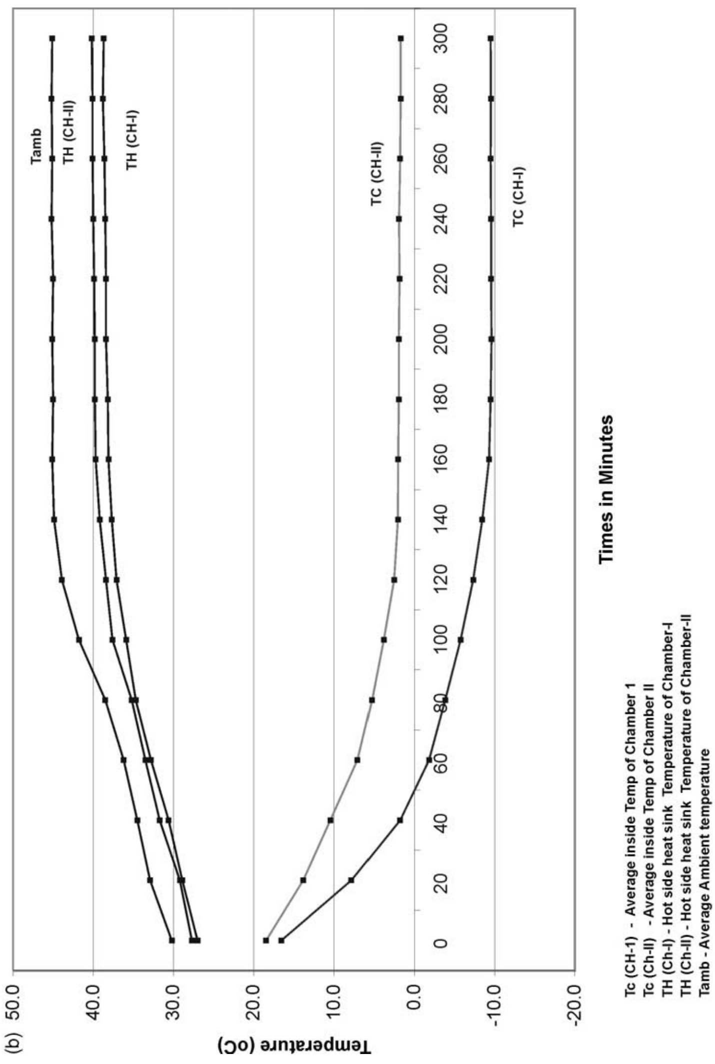

Fig. 5. (*continued*)

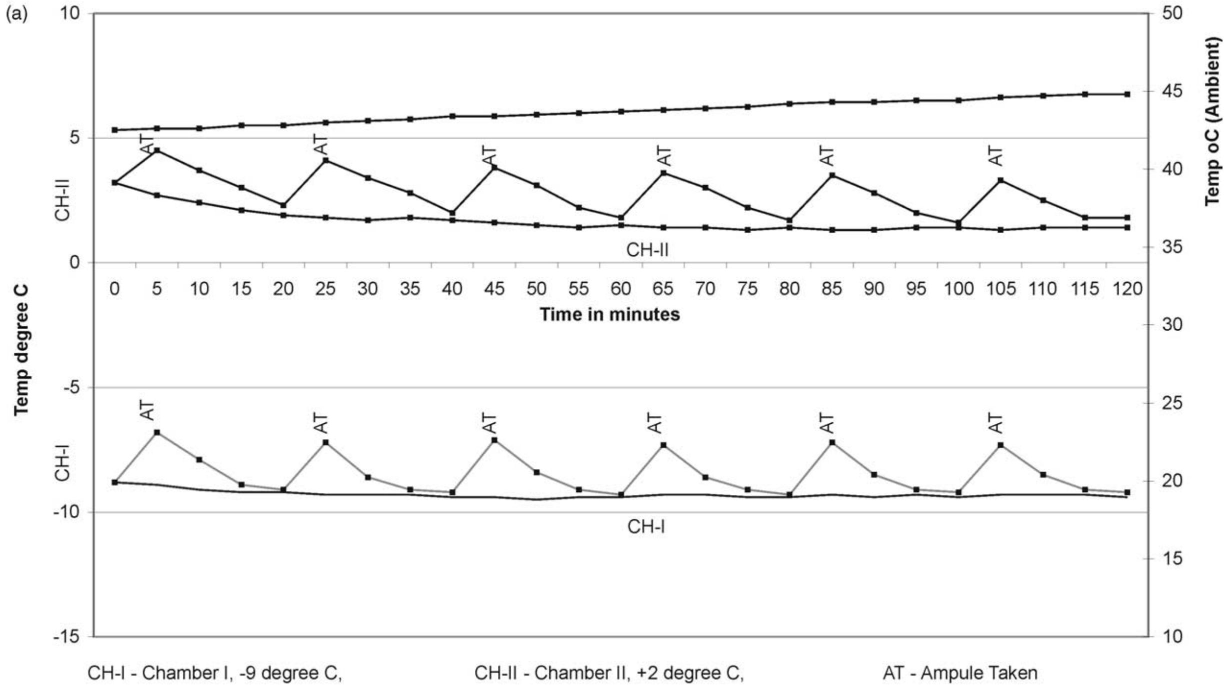

Fig. 6. (a) Typical test results with −9 and +2 °C double door thermoelectric cold-chain chest. Case study during opening and closing the chamber, with three-quarters of chamber filled with ampules (result recorded after reaching the desired temperature); (b) typical test results with −9 and +2 °C double door thermoelectric cold chain chest. Case study during opening and closing the chamber, only two ampules inside each chamber (when desired temperature reached).

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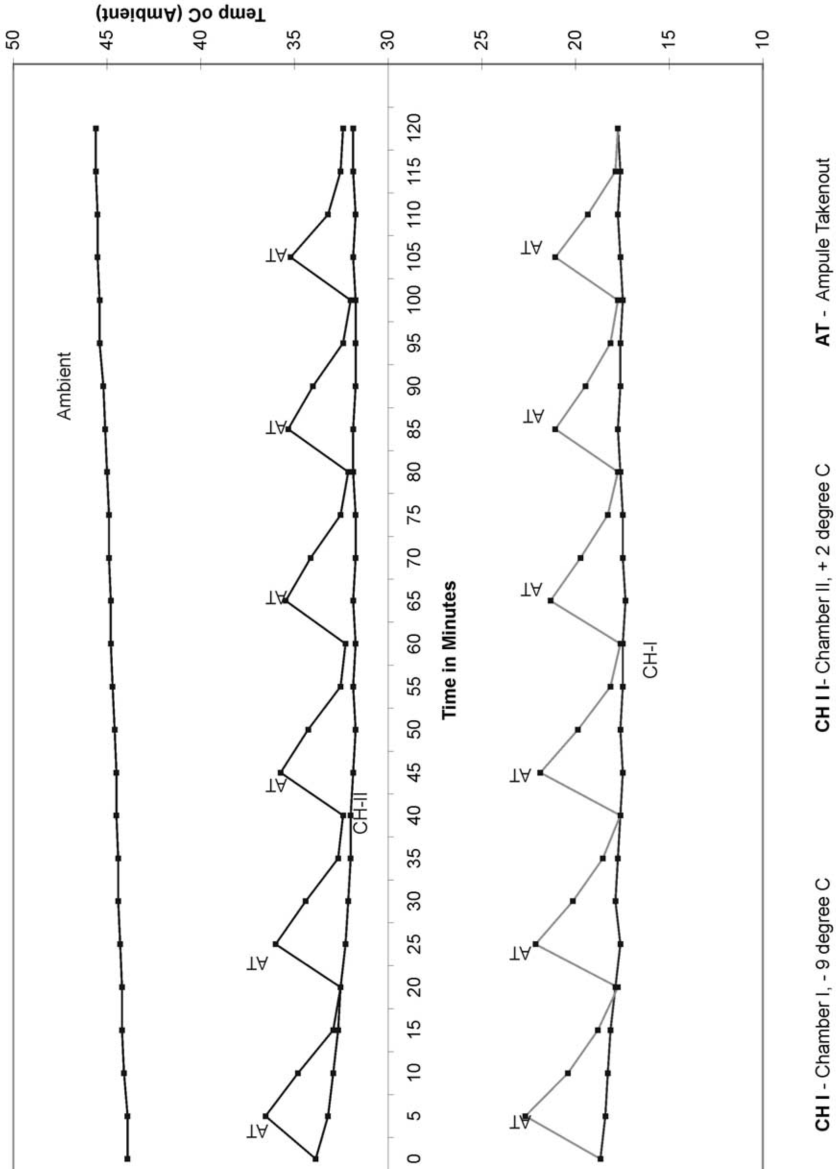

Fig. 6. (*continued*)

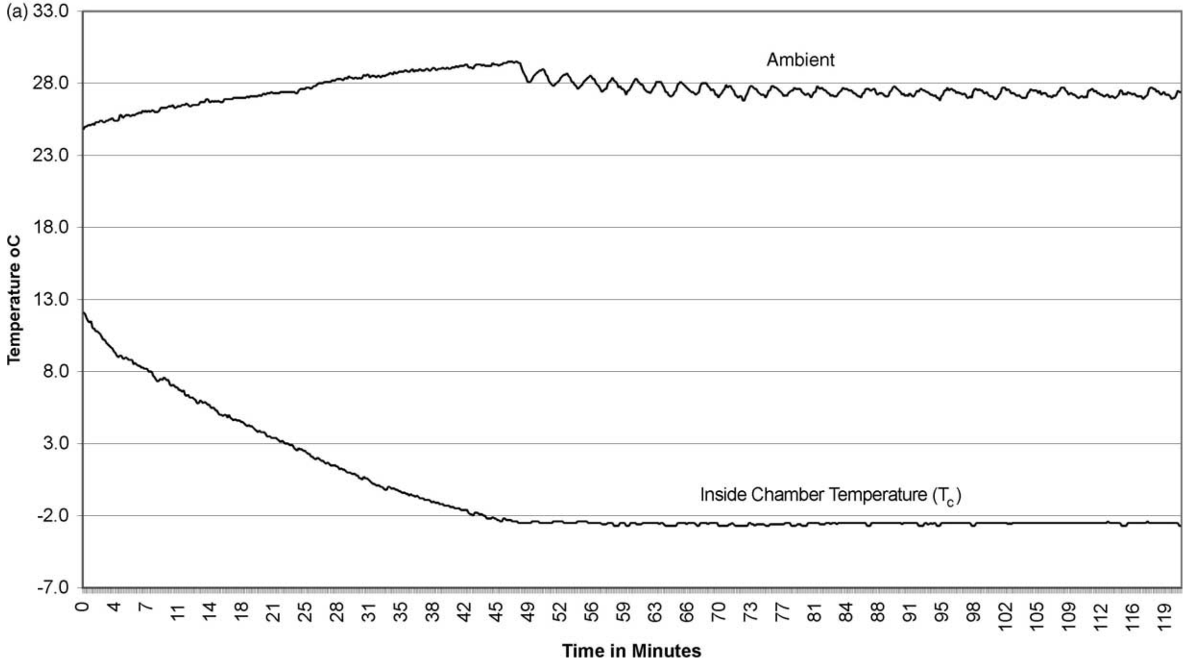

Fig. 7. (a) Typical test results of electronic circuit fixed with −9 °C chamber with reference to the ambient temperature, (b) typical test results of electronic circuit fixed with −9°C chamber with reference to ambient temp at that instant (after reaching the desired temperature).

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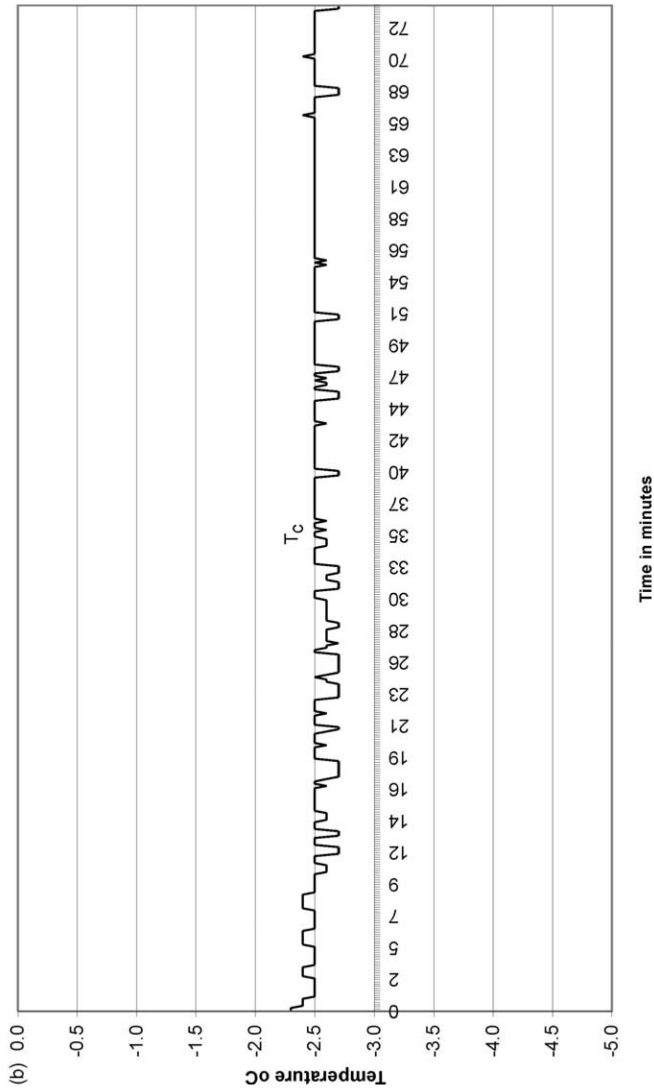

Fig. 7. (*continued*)

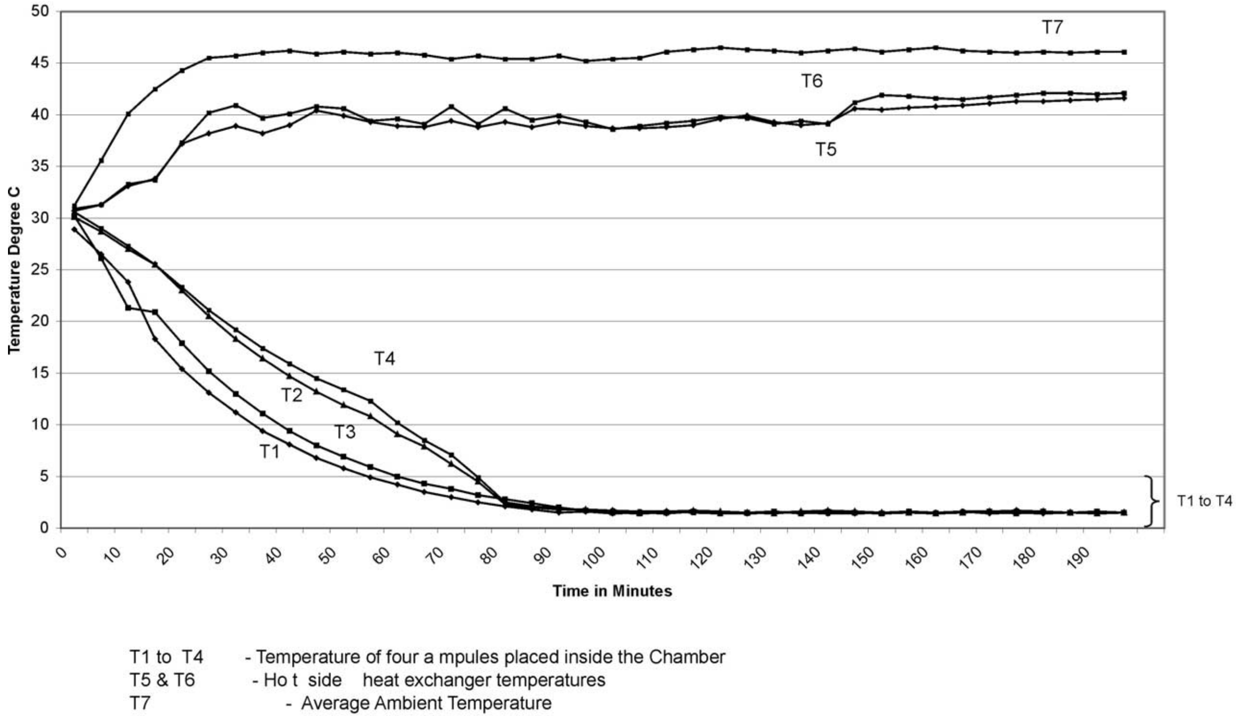

Fig. 8. Typical results of single door +2 °C thermoelectric cold-chain chest.

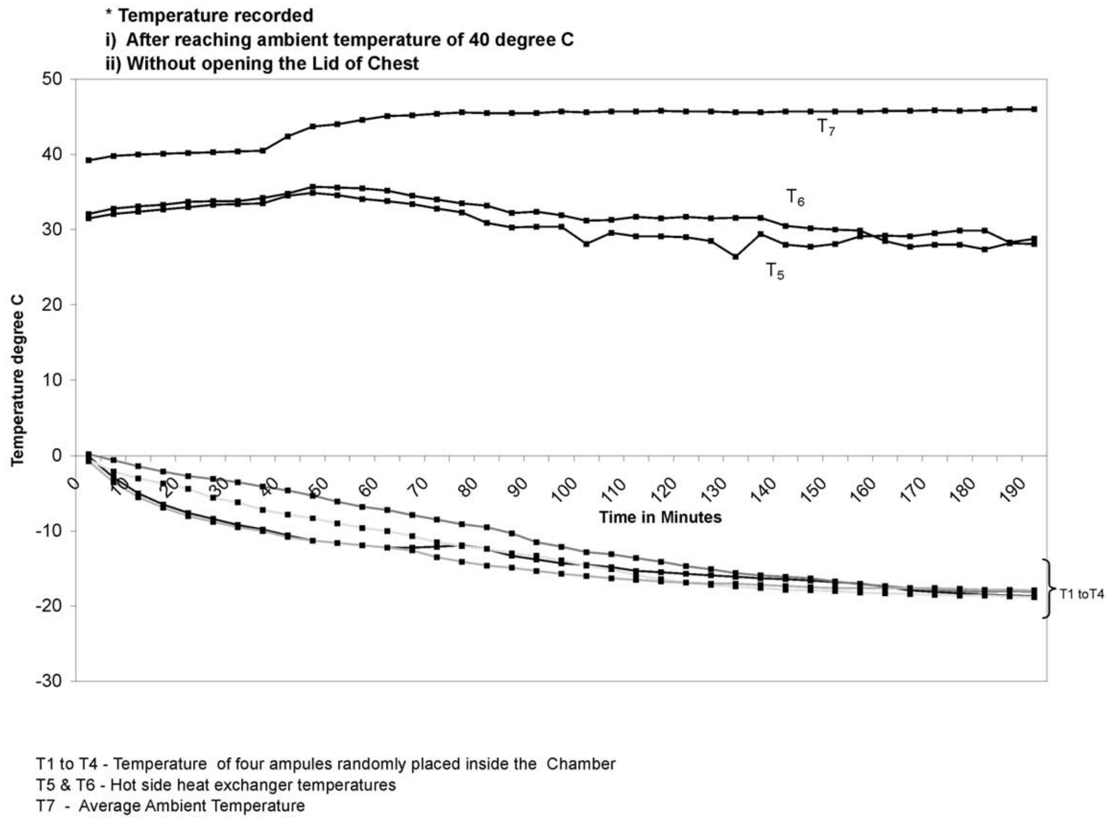

Fig. 9. Typical results of single door −17 °C thermoelectric cold-chain chest.

Fig. 5b represents the average temperature versus time characteristic of −9 °C and + 2 °C double-door thermoelectric cold chain chest in an ambient environment of 45 °C.

Fig. 6(a) and (b) represents typical average test results for the temperature versus time of a−9 °C and + 2 °C double-door thermoelectric cold-chain chest, during the opening and closing the lid of the respective chamber (simulating the field conditions of taking out the ampules from the chamber) under two different conditions: a) 3/4 of the chamber is filled with ampules and b) only two ampules are inside the chamber. The objective of conducting such experiments was to observe how the temperatures inside the chambers were changing with time when the chambers were full and also when they were almost empty. It is seen that, in both the chests (i.e. + 2 °C and −9 °C TCCs), by opening the lid, the maximum temperature of the ampules only rose by + 3 °C with respect to the desired temperature, which does not affect the potency of the vaccine.

By adjusting the set point of the temperature controller, the temperature in the −9 °C chamber can be maintained at some intermediate temperature between −9 °C and + 2 °C. Fig. 7(a) and (b) represents typical average test results of the temperature versus time of the −9 °C chamber with the corresponding temperature controller set for −3 °C. It is seen that the set temperature (−3 °C) is maintained almost uniformly. Thus the temperature controller gives additional flexibility in terms of end use. These circuits also reduce the overall power consumption after reaching the set temperature.

Typical results (of temperature versus time) of the Type I single-door (+ 2 °C thermoelectric cold-chain chest (Fig. 8) show that the temperature of four ampules randomly placed in the chest had reached + 2 °C after 80 min and was maintained until the end of the experiment i.e. up to 200 min. The initial current requirement was 6.8 amps operated at 12 V DC. After reaching the desired temperature (i.e. + 2 °C), the temperature controller connected with the thermoelectric modules reduced the current of the modules to one-third of its full current until the inside temperature again had risen up to + 3 °C.

After reaching the desired temperature, results show that the temperatures at each corner of the chest are almost identical. The hot-side heat-exchanger temperatures are seen to be fluctuating due to the uneven forced convection.

Typical results (for temperature versus time) for Type III single-door −17 °C thermoelectric cold-chain chests are shown in Fig. 9. The temperature was recorded after reaching an ambient of 40 °C without opening the lid of the chests. From the experiment, it was observed that a total 8.4 amp current was required for reaching −17 °C for both double-stage thermoelectric modules (as mentioned above). After reaching the desired temperature, the current was reduced to one-third of its full value. It was also observed that the inside temperature was in the range of −15 °C to −18 °C. Such a variation inside the chest may be due to the rapid heat gain under steep temperature gradients.

4. Conclusion

Theremoelectric cold-chain chests described above are an important link that needs to be maintained to ensure the full potency of important vaccines. The TCCs

are portable devices operated by 12 V DC power, which may be provided by a vehicle battery.

TCCs have been designed and tested for maintaining chamber temperatures of 2 °C, −9 °C and −17 °C under the ambient conditions up to 45 °C. A dual chamber TCC has also been desired in which vaccines requiring a stage at +2 °C can be stored along with vaccines requiring storage at −9 °C.

The cooling effect is provided by thermoelectric modules available on the market. Optimal selection of the module has been a critical part of the design as also the assembly of the module with a cold/hot side exchanger, cooling fan and spacer block.

The TCCs are provided with electronic controllers that adjust the current supply to the modules to maintain the chamber temperature within of the specified range.

Proper placement of the thermoelectric modules ensures a more uniform distribution of temperature across the chamber.

Tests carried out to evaluate the variation of the chamber temperature when the chests are opened for extracting a vaccine ampoule have confirmed that the chamber temperature is maintained within 3 °C even under such conditions.

NiMH batteries fixed on the TCCs ensure an uninterrupted power supply for up to 60 min during transit from a medical centre/sub-centre to the vehicle.

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